

NOAA's Sensing Hazards with Operational Unmanned Technology (SHOUT) Experiment Observations and Forecast Impacts

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ABSTRACT: The National Oceanic and Atmospheric Administration's (NOAA) Sensing Hazards with Operational Unmanned Technology (SHOUT) project evaluated the ability of observations from high-altitude unmanned aircraft to improve forecasts of high-impact weather events like tropical cyclones or mitigate potential degradation of forecasts in the event of a future gap in satellite coverage. During three field campaigns conducted in 2015 and 2016, the National Aeronautics and Space Administration (NASA) Global Hawk, instrumented with GPS dropwindsondes and remote sensors, flew 15 missions sampling 6 tropical cyclones and 3 winter storms. Missions were designed using novel techniques to target sampling regions where high model forecast uncertainty and a high sensitivity to additional observations existed. Data from the flights were examined in real time by operational forecasters, assimilated in operational weather forecast models, and applied postmission to a broad suite of data impact studies. Results from the analyses spanning different models and assimilation schemes, though limited in number, consistently demonstrate the potential for a positive forecast impact from the observations, both with and without a gap in satellite coverage. The analyses with the then-operational modeling system demonstrated large forecast improvements near 15% for tropical cyclone track at a 72-h lead time when the observations were added to the otherwise complete observing system. While future decisions regarding use of the Global Hawk platform will include budgetary considerations, and more observations are required to enhance statistical significance, the scientific results support the potential merit of the observations. This article provides an overview of the missions flown, observational approach, and highlights from the completed and ongoing data impact studies.

<https://doi.org/10.1175/BAMS-D-18-0257.1>

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In final form 21 January 2020

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Accurate forecasting of high-impact weather events like tropical cyclones (TCs) is one of the most critically needed capabilities of weather services around the world. While significant progress has been made toward improving the quality of the forecasts, skill remains limited in some respects (e.g., TC intensity), and recent government spending directives and scientific management decisions continue to prioritize research activities and investments to further increase forecast accuracy. Efforts to improve forecasts can follow several different paths. The components of the numerical weather prediction (NWP) system can be thought to include 1) input observations, 2) the data assimilation method used to merge those observations with model fields, and 3) the actual forecast model (e.g., Wang et al. 2019). The relative contribution of the different components to forecast improvements can vary depending on the event and specific forecast system and can evolve with time. Focusing on the inputs, observations are currently assimilated from a wide range of observing systems to help improve forecast accuracy. Environmental satellites compose a critical backbone of this observing system, and each year many dedicated missions using manned aircraft are conducted to collect supplemental observations of tropical disturbances and TCs.

The unique capabilities of high-altitude, long-endurance (HALE) unmanned aircraft systems (UAS) like the Global Hawk (GH) offer an important new potential for further complementing and enhancing observations of high-impact weather events. An early vision of the potential application of HALE UAS for weather and climate prediction was presented by MacDonald (2005). While the capabilities of the GH for novel weather research applications was successfully demonstrated in the National Aeronautics and Space Administration (NASA)-led Genesis and Rapid Intensification Processes (GRIP; Braun et al. 2013) and Hurricane and Severe Storm Sentinel (HS3; Braun et al. 2016) experiments, and the National Oceanic and Atmospheric Administration (NOAA)-led Winter Storms and Pacific Atmospheric Rivers (WISPAR) investigation, those projects did not explicitly evaluate the potential impacts of GH observations on operational weather forecasting.

Since satellite data play such a key role in the delivery of accurate weather forecasts, any gap in the environmental satellite system creates a potential risk to the overall quality of the forecasts. The range and endurance of HALE UAS provide a capability well suited for temporarily supplementing missing satellite observations over limited priority regions. In response to these factors, the Sensing Hazards with Operational Unmanned Technology (SHOUT) project was initiated by the NOAA UAS Program under support from the Disaster

Relief Appropriations Act of 2013. The original overarching goal of SHOUT was to demonstrate and test a prototype UAS concept of operations that could be used to mitigate the risk of diminished accuracy of high-impact weather forecasts and warnings in the case of polar-orbiting satellite observing gaps. At the time, there was concern about the potential for a gap in coverage between the *Suomi National Polar-Orbiting Partnership (Suomi NPP)* and *Joint Polar Satellite System-1 (JPSS-1)* satellites. Fortunately, the gap did not occur, and the project more generally explored the value of the UAS data as a complement to the present suite of observing systems.

Guided by these goals, the SHOUT project focused on two specific objectives:

- 1) Quantify the impact of UAS observations on high-impact weather prediction through data impact studies using observing system experiments (OSEs), based on observations collected during prototype operational field missions, and observing system simulation experiments (OSSEs), based on simulated observing capabilities.
- 2) Assess the operational effectiveness of UAS through performance of a cost–benefit analysis.

To support these objectives, NOAA partnered with NASA and supported dedicated field campaigns, diverse data impact studies by various analysis teams, and development of detailed cost and operational effectiveness analyses. This paper summarizes the SHOUT observational approach and impact analyses completed thus far in response to objective 1. The paper additionally discusses some of the successes and challenges in attempting to employ the GH in an operational-type manner. In further fulfillment of objective 2, an analysis of the costs, staffing, and logistical requirements associated with operational utilization of the GH was presented in a report by Kenul et al. (2018).

SHOUT operations and observations

Assessing the potential of a new observing system to positively impact weather forecasts requires a large amount of representative observations to input into the forecast system. While OSSEs provide a powerful capability to test impacts from simulated observations and were an integral component of the SHOUT project, data denial studies with actual observations remain an important component of complete evaluations. To support the analysis of the impact of observations from HALE UAS on forecasts of high-impact weather events, the SHOUT project conducted three field campaigns from 2015 to 2016, collecting environmental observations from the GH.

The events sampled included TCs and landfalling Pacific winter storms. TCs, especially hurricanes, are among the most potentially destructive high-impact weather events and pose a significant forecasting challenge. Major winter storms over the Pacific Ocean and atmospheric river events that make landfall and bring strong winds and extreme precipitation to the U.S. West Coast and Alaska are also important to forecast accurately because of their societal impact in those regions (e.g., Langland et al. 1999; Ralph et al. 2006; Ralph and Dettinger 2012). SHOUT deployments targeting TCs included the 2015 Hurricanes and 2016 Hurricane Rapid Response (HRR) field campaigns. The third campaign explored the impact of winter storms during February 2016 in partnership with the NOAA El Niño Rapid Response (ENRR) experiment (Dole et al. 2018).

In addition to these dedicated campaigns, SHOUT also partnered with, and utilized data collected during, the HS3 investigation in 2012–14 and the NASA Eastern Pacific Origins and Characteristics of Hurricanes (EPOCH; Emory et al. 2015) experiment in 2017. The NOAA UAS Program provided additional funding to NASA for a fifth week of operations in HS3 in 2014 and up to three additional science flights during EPOCH. NOAA was given the discretion to lead those additional EPOCH flights to continue and extend the SHOUT objectives.

Global Hawk aircraft and instrument payload. The NASA GH was the UAS utilized in all SHOUT field campaigns for multiple reasons including the aircraft's capability, technological maturity, availability of previously integrated and proven sensors of relevance, and potential availability for future operational use. SHOUT specifically used NASA's Air Vehicle Six (AV-6), a developmental version of the Northrop Grumman GH aircraft. Key aircraft capabilities are its flight duration of roughly 24 h, operating altitudes of 16,765–19,810 m (55,000–65,000 ft), and payload capacity of 680 kg (1,500 pounds). The aircraft cruises at approximately 620 km h⁻¹ (335 kt). Instrument communications and data return are available via both Iridium and Ku-band systems. High data rates provided through Ku-band satellite communications facilitate real-time data utilization, even for larger-volume data streams from remote sensors.

The instrumentation deployed on the GH during SHOUT included in situ and remote sensing payloads to measure pressure, temperature, moisture, precipitation, winds, and electric fields both within storms and in their surrounding environments. The primary instrument set included the Airborne Vertical Atmospheric Profiling System (AVAPS), High-Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer (HAMSR), and High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP). The Lightning Instrument Package (LIP) was additionally deployed during the 2015 SHOUT Hurricanes campaign. A photograph of the GH with the SHOUT payloads is shown in Fig. 1.

The primary selection criteria for the payloads were their potential to support improvements in TC forecasts and the requirement that they had been flown on the aircraft before. The GH AVAPS dropwindsonde system (Wick et al. 2018a) carries up to 90 GPS dropwindsondes (dropsondes; Hock and Franklin 1999) providing high-vertical-resolution measurements of pressure, temperature, and humidity (2-Hz sampling rate), as well as wind speed and direction (4-Hz sampling rate). Dropsondes were included on the GH payload because of their operational utilization from other aircraft and demonstrated potential for positive impact on TC forecasts (Aberson 2010). HAMSR, a cross-track scanning passive microwave radiometer (Brown et al. 2011) developed by the NASA Jet Propulsion Laboratory, retrieves vertical profiles of atmospheric temperature and humidity in a similar manner to the Advanced Microwave Sounding Unit (AMSU) aboard NOAA polar orbiting satellites. HAMSR was selected primarily because of the large positive impact of AMSU profiles on NWP forecasts (e.g., Gelaro et al. 2010) and the original satellite data gap mitigation focus of the SHOUT project, which argued for similar capabilities. HIWRAP, a dual-frequency, conically scanning Doppler radar supported by the NASA Goddard Space Flight Center (Li et al. 2011) provides information on precipitation, three-dimensional winds within precipitating areas, and ocean vector winds. Its inclusion was based on the demonstrated utility of the tail Doppler radar on the NOAA WP-3Ds (Aksoy et al. 2013; Aberson et al. 2015) and previous positive HIWRAP research results (Sippel et al. 2014). LIP, providing electric field measurements in the vicinity of the GH (Hood et al. 2006), was included primarily for extra situational awareness and hazard avoidance (e.g., aircraft proximity to active areas of lightning). Additional details on the payloads are summarized in Table 1 and by Dunion et al. (2018).



Fig. 1. Photograph of the NASA GH aircraft instrumented for the SHOUT campaigns. Key payloads visible include HAMSR (under nose), HIWRAP (center, main payload bay), AVAPS dropsonde launcher (underside of tail), and LIP (sensors on top of engine nacelle and elsewhere around aircraft). (Photograph courtesy NASA).

Table 1. SHOUT payload characteristics.

Instrument	Measured/retrieved variables	Resolution		Spatial extent
		Horizontal	Vertical	
Dropsondes	Vertical profiles of pressure, temperature, humidity, and winds	Point	~3 m (wind), ~6 m (other) at surface	Drifting single-point profile
HAMSR	Brightness temperatures, 3D distribution of temperature, water vapor, and cloud liquid water	~2 km (nadir)	~2 km	Cross-track slice with ~40-km surface swath
HIWRAP	Reflectivity, 3D winds, and precipitation	~1 km	~60 m	30° and 40° cones beneath aircraft
LIP	Electric field, lightning statistics, and air conductivity	Point	—	Inferred lightning in variable radius around aircraft

SHOUT field campaign highlights. The dedicated SHOUT field campaigns included 15 GH missions in 2015–16. Three flights targeting two TCs were flown during the 2015 Hurricanes campaign, and nine flights studying four named TCs were flown during the 2016 HRR campaign. An additional three missions targeting Pacific winter storms were flown in February 2016 during the ENRR experiment. A total of 826 dropsondes were deployed over 356 flight hours. Maps of the flight tracks are shown in Fig. 2, and key details are summarized in Table 2. This section provides a broad overview of the campaigns and selected highlights. Additional descriptions of the missions flown are contained in the SHOUT field campaign summary report (Dunion et al. 2018).

TCs: 2015 HURRICANES AND 2016 HRR. Due to their large societal impacts, SHOUT focused on TCs as the primary high-impact weather events for observation and forecast analysis. The idealized goal for the 2015 and 2016 campaigns was to conduct missions associated with storms where significant forecast uncertainty existed or where there was potential for high societal impact, and sampling strategies were designed to improve the impact of the data on the forecasts. Atlantic storms were further prioritized based on the assumption of higher potential forecast uncertainty and the greater potential impacts on U.S. coastal populations. The reality of any field campaign with a finite operational period is that one is limited to the study of events occurring during that period. While TCs are high impact as a class of events, not all the storms sampled had a direct high impact on the United States.

To collect observations to improve TC forecasts, and specifically those of TC track and intensity, targeting strategies based on identification of regions of greatest forecast sensitivity were employed (see “Targeted observations in SHOUT” sidebar). Flight plans were constructed by SHOUT mission scientists based on guidance from the targeting computations,

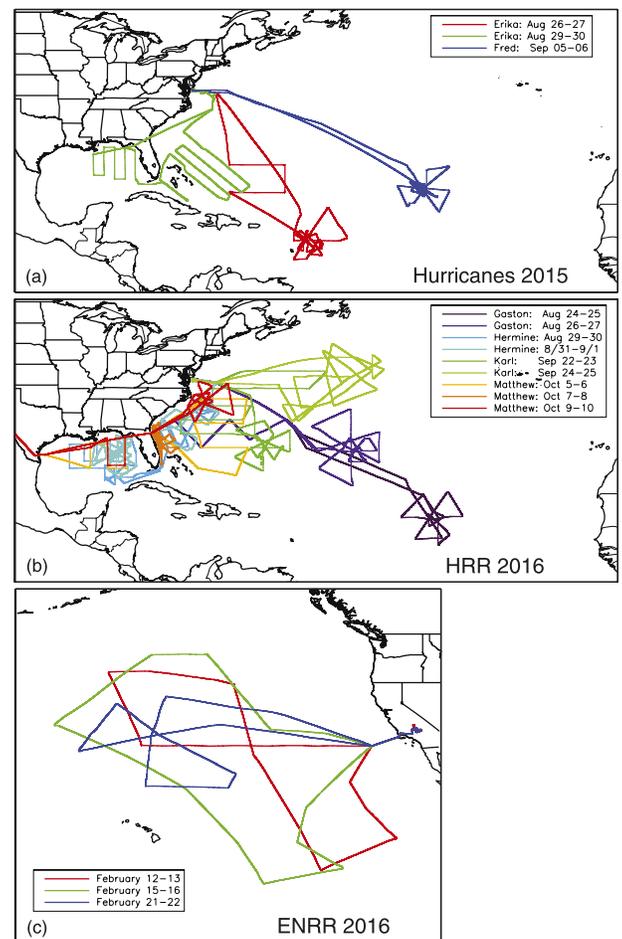


Fig. 2. Maps of the flight tracks flown by the NASA GH during each of the three SHOUT campaigns: (a) Hurricanes 2015, (b) HRR 2016, and (c) ENRR 2016. Distinct flights are denoted by the different colors as indicated in the legends.

Table 2. Summary of SHOUT flights.

Campaign	Dates	Target	Duration (h)	Dropsondes deployed
2015 Hurricanes	26–27 Aug	Erika [tropical storm (TS)]	23.7	14
	29–30 Aug	Erika (dissipated)	23.7	58
	5–6 Sep	Fred [tropical depression (TD)]	24.0	16
2016 ENRR	12–13 Feb	Atmospheric river impacts in the Pacific Northwest and British Columbia	22.9	2
	15–16 Feb	Trough interactions and a cutoff low pressure system in advance of a Southern California precipitation event	24.5	22
	21–22 Feb	Dual precipitation and high wind event impacts in Alaska and the southeastern United States	23.6	66
2016 HRR	24–25 Aug	Gaston (TS/hurricane)	23.9	85
	26–27 Aug	Gaston (TS/hurricane)	23.8	55
	29–30 Aug	Hermine (TD)	23.8	90
	31 Aug–1 Sep	Hermine (TS/hurricane)	22.8	87
	22–23 Sep	Karl (TD/TS)	24.0	82
	24–25 Sep	Karl (TS)	22.8	81
	5–6 Oct	Matthew (hurricane, category 3)	24.7	62
	7–8 Oct	Matthew (hurricane, category 2/3)	23.7	43
9–10 Oct	Matthew (Extratropical)	24.8	63	

storm characteristics, and other inputs from the operational community [e.g., NOAA Environmental Modeling Center (EMC) and National Hurricane Center (NHC)]. The primary flight plan element employed for the TC flights was variably sized rotated butterfly patterns (see partial example in Fig. 3 with two of the three normal branches) centered on the expected storm position. The storm’s intensity was typically predicted to be most sensitive to observations near the inner core of the system (as illustrated in Fig. SB1). Sampling directly over the storms was also prioritized to take advantage of the observations provided by the remote sensing payloads. The butterfly pattern emphasizes such sampling of the storm center and provides good azimuthal and radial distributions of observations surrounding the storm. The orientation of the butterfly patterns was designed subjectively based on the storm characteristics and guidance provided by the forecast sensitivity calculations. Any information on storm quadrants with increased forecast sensitivity was used in the design. Flight plans typically included butterfly patterns with both small (~225 km) and large (~450 km) leg lengths to balance the sampling of the storm center and surrounding regions. The route of transit to the storm and additional sampling

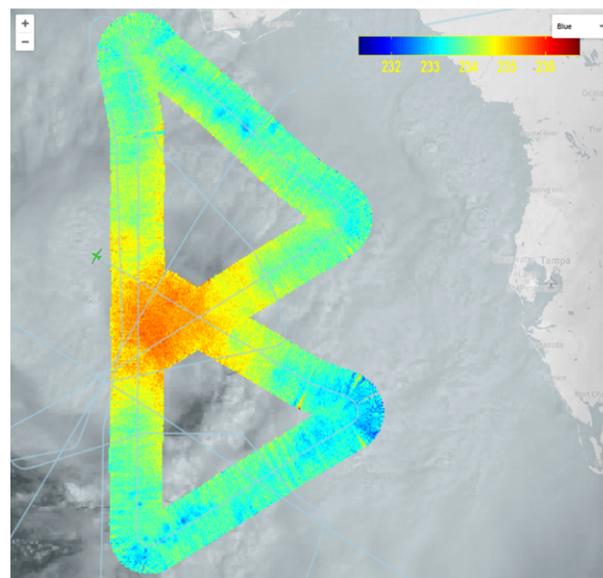


Fig. 3. HAMSr observations at a frequency of 54.94 GHz illustrating the warm-core structure of Hermine just prior to its classification as a hurricane. The colors indicate the brightness temperature (K) and are representative of the atmospheric temperature at about 250 hPa. The observations were collected on 1 Sep 2016 (concluding around 1700 UTC) during the second GH mission studying Hermine. Graphic generated within the NASA Mission Tools Suite and provided by Shannon Brown from NASA JPL.

displaced from the storm center were based heavily on the forecast track sensitivity results. The incorporation of guidance on additional regions for sampling provided by NHC for some flights is evidence of the collaboration of SHOUT with operational activities and provides a model of how the GH could potentially be used as an operational platform in the future.

SHOUT conducted flights at different times from both the NASA Armstrong Flight Research Center (AFRC) in California, the aircraft's home base, and a forward-deployed base at NASA Wallops Flight Facility (WFF) in Virginia. Operations from WFF were favored scientifically because of the greater time on station for Atlantic basin storms and greater operational flexibility; however, this base of operations resulted in higher mission costs, and the inability to sample eastern Pacific cyclones due to limitations on GH flights over land. By contrast, basing

Targeted observations in SHOUT

The SHOUT GH missions were designed with the goal of collecting data that could be used to improve forecasts and reduce forecast uncertainty. To accomplish this, targeting strategies were employed during each campaign and the guidance subjectively incorporated in the flight plan design. The methods focused on identifying the regions of greatest forecast sensitivity—that is, where the forecast outcome (typically TC position and intensity) is most sensitive to environmental conditions and, thus, where it might be advantageous to deploy additional observations.

For the TC missions, a real-time technique for targeting GH dropsonde observations in the TC environment was developed at the University at Albany, State University of New York. This TC targeting algorithm, employing an ensemble-based sensitivity algorithm, identifies regions where high model forecast uncertainty (e.g., track or intensity) and a high sensitivity to assimilating additional observations (e.g., dropsonde data) exists (Torn 2014). Model input includes 80-member HWRF ensemble forecasts made available through NOAA EMC and in 2016, the calculations were repeated with the ECMWF ensemble. Once the forecasts were completed, sensitivity and target location calculations were carried out to identify locations where assimilating GPS dropsonde data at a specific time might decrease the ensemble variance in forecasted TC track and/or intensity at a specified time in the future. The targeted lead time for achieving forecast improvements was in the 2–3-day range, depending on specifics of the storm and operational GH constraints.

Examples of the computed sensitivity maps used in planning a flight into Tropical Storm Erika in 2015 are shown in Fig. SB1. In the graphics, warm colors indicate locations where the dropsonde observations are expected to have the largest reduction in the forecast variability. While impact on the intensity forecasts was generally greatest near the TC center, guidance on track forecast impact was often associated with larger-scale circulation patterns. During Tropical Storm Erika, the targeting guidance highlighted the importance of having an accurate estimate of a subtropical ridge to the north of the storm early in its life cycle and a trough over the Gulf of Mexico during its dissipation stage.

For the winter storm missions, an Ensemble Transform Sensitivity (ETS) methodology (Zhang et al. 2016; Wang et al. 2018) was used to identify prioritized regions for sampling. In the ETS method, the gradient of the forecast error variance to analysis error variance is calculated for each predefined verification region. The ETS technique used an ensemble of 80 forecasts from the NOAA operational Global Ensemble Forecast System. The sensitivity metric was based on a dry total energy norm using temperature and zonal and meridional winds at pressure levels of 200, 500, and 700 hPa. The ETS methodology was similar in approach to that employed in the former operational Winter Storm Reconnaissance program, but used the current operational forecast system.

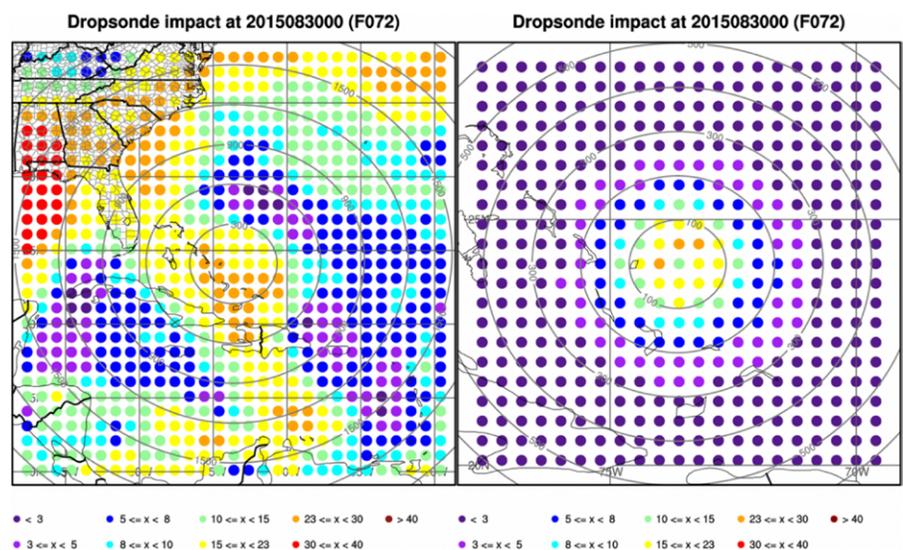


Fig. SB1. Example HWRF targeting guidance showing computed sensitivity for Tropical Storm Erika's (left) position and (right) intensity. Numerical values represent the percentage reduction in forecast variance resulting from assimilation of a hypothetical GPS dropsonde observation on the 72-h forecast valid at 0000 UTC 30 Aug 2015. Range rings reflect the distance from the TC center at the presented time of impact.

at AFRC allowed for potential observation of eastern North Pacific cyclones, and sampling of Atlantic basin storms was still possible, albeit with reduced duration.

The 2015 season was particularly challenging for a field campaign targeting TCs. A strong developing El Niño event was expected to damp TC activity in the Atlantic basin. SHOUT initially elected to operate the Hurricanes 2015 campaign from WFF because of the prioritization of any Atlantic storms, but only conducted three missions, which observed named storms Erika and Fred. While Erika was initially viewed as a potential threat for landfall in Florida, and Fred's intensity was variable and challenging to forecast leading up to the SHOUT mission, the collected observations were ultimately not fully ideal for the forecast impact assessments. Operations were shifted to AFRC after two weeks in the hope of capturing additional systems in the eastern Pacific, but the GH was damaged in a ground-handling incident, and no further missions were possible in 2015.

The 2016 HRR campaign was more successful both in providing a larger number of observations and in sampling storms with high impacts to the United States. Nine flights observed four different named storms (see Table 2), including two landfalls. Hurricanes Hermine and Matthew were particularly impactful to the United States. Hermine was sampled twice with consecutive flights during its intensification prior to landfall in Florida. An illustration of HAMS observations of Tropical Storm Hermine during the second GH flight in Fig. 3 shows the ability of the observations to resolve the warm-core structure of the storm in real time. Hurricane Matthew was sampled with three back-to-back (i.e., three flights flown every other day for six days) missions providing observations leading up to and during its path along the southeastern United States. These observations were pursued to evaluate the forecast track uncertainty and associated questions of whether the storm would make landfall in the United States. The progression of the dropsonde observations and their position relative to the storm position and nested domains of the operational Hurricane Weather Research and Forecasting Model (HWRF) used in the impact studies is shown in Fig. 4. The forecast impact of these observations is discussed below. The sampling

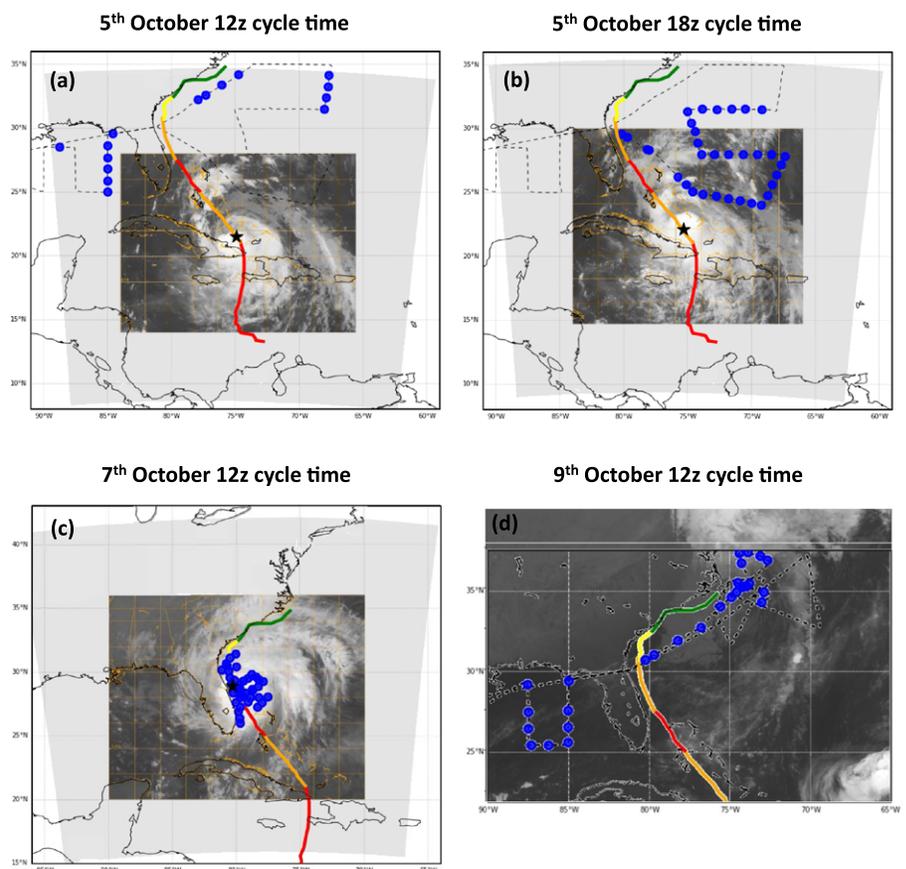


Fig. 4. Dropsonde sampling of Hurricane Matthew illustrating the observation position relative to the storm and HWRF model cycle in which the data were assimilated: (a) 1200 UTC 5 Oct, (b) 1800 UTC 5 Oct, (c) 1200 UTC 7 Oct, and (d) 1200 UTC 9 Oct 2016. Launch positions of dropsondes assimilated in the indicated cycles are denoted with blue circles. The track of the storm is color coded by intensity (green, category 1; yellow, category 2; orange, category 3; red, category 4) and the storm center at the corresponding time denoted with a star. Coincident satellite imagery is visible reflectance from GOES East. The gray shading in (a)–(c) represents the HWRF d02 storm-following domain for the cycle. Note that (d) shows a smaller region that falls within the model domain. Graphics generated and provided by James Taylor.

of Matthew was particularly significant since the campaign was extended past its scheduled completion date to enable the flights, which were launched from AFRC for cost savings. Among the other storms sampled, although Hurricane Gaston remained over open water of the North Atlantic throughout its life cycle, uncertainty regarding its precise location of recurvature and the lack of any other concurrent aircraft observations made its observations valuable for the subsequent impact studies.

The 2016 HRR campaign adopted a rapid response model to maximize the opportunity for capturing suitable scientific targets, reduce costs, and demonstrate a mission concept for future potential operational surveillance and reconnaissance flights of the GH. With the exception of aircraft personnel and one member of the AVAPS team, the staff was deployed and supported the missions with as little as 48-h notice, minimizing deployment costs. Initial deployment of the GH to WFF was also delayed until Atlantic storm activity of interest seemed likely. Improvements in operational efficiency were further achieved through reduced staffing and increased remote participation by the SHOUT science and forecast teams. With the reduced costs, the campaign was able to operate over an extended 2-month period and ultimately be further extended to enable the sampling of Hurricane Matthew on a budget that would have traditionally supported just a 4–5-week fixed campaign.

Collaborations played an important part of the SHOUT operations. During 2015, SHOUT collaborated with the Office of Naval Research (ONR) Tropical Cyclone Intensity (TCI) experiment that employed the NASA WB-57 high-altitude aircraft to collect observations in the TC outflow layer (Doyle et al. 2017). While the two experiments did not fly coordinated missions into a common storm, the SHOUT data impact analyses are incorporating WB-57 observations from the Hurricane Imaging Radiometer (HIRAD; Cecil and Biswas 2017) since that had been another primary candidate payload for SHOUT. In 2016, there was significant coordination with operational Air Force and NOAA aircraft, the NOAA Hurricane Intensity Forecasting Experiment (IFEX; Rogers et al. 2013), and the international North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX; Schäfler et al. 2018) during Tropical Storm Karl. Together, the observations from all the aircraft provided unique sampling of a complex storm over its lifetime.

WINTER STORMS: 2016 ENRR. Collaboration with the ENRR experiment provided SHOUT with an opportunity to add the investigation of potential forecast improvement of major Pacific winter storms to its impact study topics. The original goal of the deployment was to explore the ability of GH observations to improve forecasts of major precipitation events anticipated to impact California during the strong 2016 El Niño event. Since the storms that actually occurred during the experiment period had less impact on California than was climatologically expected, the objectives were expanded to include significant precipitation and wind events affecting coastal regions of the Pacific Northwest and Alaska. Sampling was designed with the goal of improving forecasts at 2–3-day lead times. Targeting guidance was obtained using the ETS methodology (see “Targeted observations in SHOUT” sidebar) and was incorporated in mission designs that subjectively blended sampling of the most prominent associated meteorological features.

The three SHOUT ENRR missions focused on collecting observations to reduce forecast uncertainty in precipitation associated with atmospheric river events impacting the Pacific Northwest and British Columbia (flight 1) and Southern California (flight 2), and improvement of forecasts of high winds and precipitation in southern Alaska (flight 3). A major additional impact of the storm system sampled during the third flight was its later downstream effect on a severe weather outbreak in the southeastern United States. Early forecasts for the region from the Gulf coast states through the Atlantic seaboard were uncertain and wavered between a possible ice storm and severe weather outbreak until the primary upper-level trough progressed inland and was sampled by the dense operational upper-air network. Sampling

of the storm offshore provided the opportunity to evaluate the effect of the GH observations on two distinct significant weather events affecting the United States (see below and Kren et al. 2018). In addition to collaboration with the ENRR experiment, the second and third missions were flown in coordination with two Air Force Reserve Command WC-130J aircraft flying as part of an ongoing Atmospheric River Reconnaissance project led by Scripps Institution of Oceanography and NOAA EMC. While observations from a single 3-week deployment cannot yield statistically significant conclusions, the campaign enabled initial insight into the potential merit of a refined Winter Storm Reconnaissance program (e.g., Szunyogh et al. 2000) with greatly enhanced observational capabilities.

Application of SHOUT observations. The observations collected during SHOUT enabled the supported data impact assessments, and the real-time data were also used frequently by operational forecasting and modeling groups. The GH dropsonde data from all campaigns were made available to operational centers for potential assimilation into NWP models through routine, near-real-time transmission to the Global Telecommunication System (GTS). While GH dropsonde data distributed through the GTS had been assimilated operationally by the European Centre for Medium-Range Weather Forecasts (ECMWF) since HS3, the first operational assimilation of the data by NOAA occurred during SHOUT. NOAA operational assimilation of the GH data were delayed until the effectiveness of the data could be demonstrated. A significant accomplishment, the GH data were first assimilated operationally in the HWRF during the 2015 Hurricanes campaign. Because of the successful demonstration of the impact of the SHOUT data on the Global Forecast System (GFS) model (see below), operational assimilation of the GH data into the GFS model was also enabled and first occurred during the 2017 NASA EPOCH experiment, in part with additional NOAA UAS Program support to continue SHOUT objectives.

To explore potential future operational utilization of GH data, initial products were made available to NHC in real time. Specific products were prioritized based on discussions with NHC representatives, and a dedicated external SHOUT web page was implemented to host the GH data products in one location to facilitate forecaster access. Examples of real-time data products from the SHOUT sensors are shown in Fig. 5. Observations from

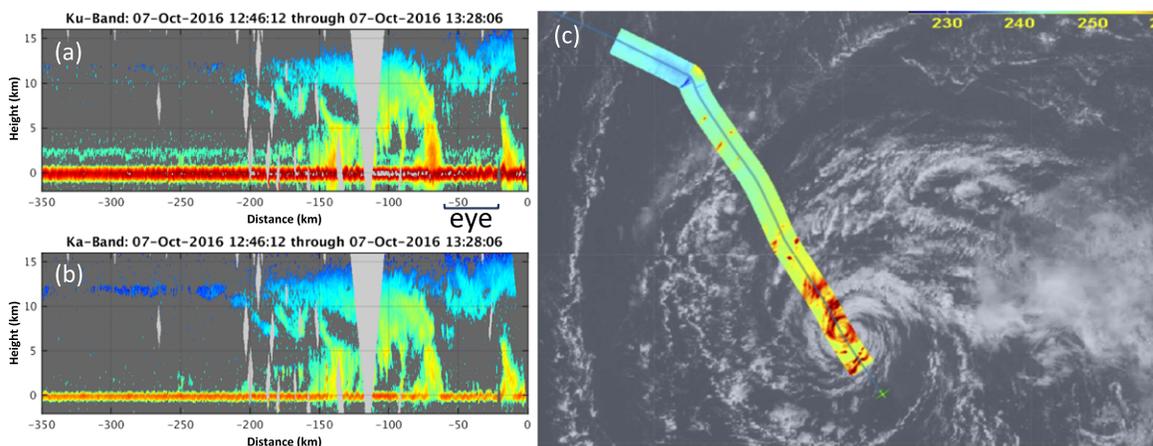


Fig. 5. Example of real-time remotely sensed imagery obtained from the NASA GH during SHOUT. (a),(b) Reflectivity cross sections from the HIWRAP at (a) Ku band and (b) Ka band during a center crossing over Hurricane Matthew on 7 Oct 2016. The position of the eye at the time of the overpass is noted on the images, and the eyewall reflectivity is clearly visible. The x axis represents distance from the aircraft's location at the concluding time of the denoted period. (c) Real-time 50.3-GHz microwave brightness temperature from the HAMSR during an overpass of Tropical Depression Fred on 5 Sep 2015. The microwave signature is highly complementary to and correlated with the visual satellite reflectance from GOES-East displayed as the background. HIWRAP imagery courtesy G. Heysmsfield at NASA Goddard; HAMSR image provided by S. Brown at NASA JPL.

the dropsondes made available through the GTS were accessed and cited frequently by NHC forecasters in their regular forecast discussions. During SHOUT HRR, 10 different forecast discussions spanning each of the 4 TCs studied made explicit mention of the GH dropsonde data. These included a case where Gaston was upgraded to a hurricane based on GH data (Fig. 6) and other instances where the data provided key storm characteristics when other aircraft were unable to readily sample the storms. Real-time graphics of products from HAMSR and HIWRAP made available via the SHOUT web page were not as extensively utilized by forecasters. Ultimately, due to the tight time constraints faced by forecasters during their shifts, more integrated and rapid access is required through existing forecaster resources.

All data currently available from the SHOUT missions can be obtained from an archive at the NOAA Physical Sciences Laboratory (PSL) (psl.noaa.gov/psd2/coastal/satres/shout_prelim_data_archive.html). New SHOUT data products will continue to be added as they become available.

GH effectiveness during SHOUT. The GH aircraft generally proved quite effective at providing the desired observations during the SHOUT campaigns. Aircraft reliability was very high and was not a significant factor in preventing the collection of desired observations (aside from the loss of use following the ground-handling accident in 2015). Payload performance was good throughout SHOUT with the exception of dropsonde launcher problems early in the 2015 Hurricanes and ENRR campaigns.

The most significant (noncost) factors impacting the use of the GH in an operational-type application were project limitations on flight over land and in non-U.S. domestic airspace, and operational limitations on the launch and recovery of the platform. Flight over U.S. land was coordinated only within preapproved regions including transit corridors. Flight in international airspace was successfully coordinated in real time directly with the country providing air traffic control services for that region. The project did not attempt to obtain permission to fly within the domestic airspace of foreign countries [within 12 nautical miles (n mi; 1 n mi = 1.852 km) of land] due to the extensive coordination and country clearance requirements. This operational limitation significantly hindered the sampling desired for optimal forecast benefit, particularly for a system like Matthew that passed over islands in the Caribbean and then came close to the U.S. coast.

Several SHOUT missions were also delayed or cancelled due to an inability to take off at the time desired. During the campaign, a chase aircraft was used for GH takeoff and landing at WFF to meet requirements to “detect and avoid” other aircraft. Weather minimum requirements for the chase of the GH created challenges during periods of low ceilings or restricted visibility, but the operational team did their best to work within the constraints. At AFRC, the external control of airfield operations by the U.S. Air Force placed severe limitations on weekend or overnight launches or recoveries. While flight near land may remain a challenge for large UAS, a basing and operational approach that ensures the ability to launch and recover when desired will be an important requirement to effectively employ the GH operationally.

Rules governing flight planning and airborne GH operations require close attention, but were generally manageable. Coordination of the GH with air traffic control has become easier

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HURRICANE GASTON DISCUSSION NUMBER 11
NWS NATIONAL HURRICANE CENTER MIAMI FL AL072016
500 AM AST THU AUG 25 2016

For much of yesterday afternoon and evening, the NASA/NOAA Global Hawk unmanned aircraft flew a mission through Gaston. On the aircraft's last pass through the storm, it released a dropsonde at 0243 UTC that measured a mean boundary layer wind of 80 kt and an average wind of 77 kt in the lowest 150 m of the sounding near the center of the cyclone. These numbers both support an intensity of 65 kt, and consequently Gaston was upgraded to a hurricane. The sonde reported a minimum pressure of 995 mb with a 69-kt surface wind, which equates to a central pressure of about 988 mb.

...

Fig. 6. Excerpt from NHC Discussion 11 for Hurricane Gaston in 2016 demonstrating real-time forecaster use of the GH data. Dropsonde data from a SHOUT mission from 24 to 25 Aug was responsible for the initial designation of the storm as a hurricane. (source: www.nhc.noaa.gov/archive/2016/al07/al072016.discus.011.shtml?).

through experience and familiarity gained in past NASA and NOAA campaigns. A basic flight plan indicating the desired flight region is required two days prior to a flight and a complete flight plan with proposed dropsonde positions one day before, but significant flight track changes could be coordinated with air traffic control throughout the flight with approximately 30-min notice. To avoid hazardous conditions associated with the storms being studied, GH flight rules place requirements on separation from significant convection and lightning. Using real-time weather data, mission scientists closely monitored these conditions and adjusted flight plans as required, but were able to do so with mostly limited impact on the desired sampling. The modification of the rules accomplished during HS3 enabled sampling that would have been impossible under standard GH weather limitations that could have required diverting around many deep cloud systems.

Operational costs for the GH were similar to other heavy research aircraft, and the costs of the 2-month 2016 HRR campaign were feasible within the program budget. Factors facilitating the demonstration included the partnership with NASA providing the GH and ground facilities and the rapid response model with delayed deployments and reduced staffing. Kenul et al. (2018) provide more details in their analysis of the cost and operational effectiveness of the GH during SHOUT.

Forecast impact of the SHOUT data

The key scientific objective of SHOUT is to evaluate the utility of GH observations to improve forecasts of high-impact weather events or mitigate potential degradation of forecasts in the event of a gap in satellite coverage. This is being accomplished by a diverse suite of studies by groups from NOAA EMC, the Hurricane Research Division (HRD) of the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML), the NOAA Global Systems Laboratory (GSL), and PSL. The studies, initial and ongoing, while generally lacking statistical significance due to the limited number of available cases, broadly suggest the potential for positive forecast benefits. Highlights capturing the breadth and observed impacts of the studies with both global and regional models are presented below. Additional details on the earliest studies are provided by Wick et al. (2018b).

Regional TC data impacts. An important component of NOAA's operational TC forecasting, particularly for storm intensity, is the regional-scale HWRF. Studies are examining the impact of SHOUT data on both operational and research versions of the model incorporating different options for data assimilation.

Of most immediate interest to NOAA operations are studies using the fully operational HWRF modeling and assimilation system. Initial evaluations at EMC employed the 2017 operational version of HWRF (H217) to examine the impact of GH dropsonde data on the model relative to operational forecasts that only assimilated routine conventional and reconnaissance observations. All dropsonde wind observations within 111 km of the storm center were excluded in this version of HWRF (in part because the transmitted data contained only the launch position and not information on the absolute position during descent). For consistency and to fully characterize the impact of the dropsonde data, the GFS model runs used to obtain the HWRF boundary conditions also either assimilated or excluded the dropsonde data, matching the treatment of the data within HWRF. Results for storms sampled in 2016 show notable positive (though not statistically significant) improvements in both track and intensity forecasts at lead times of 72 h and greater when the GH dropsonde data are added. As illustrated in Fig. 7, skill improvements are as high as 5%–10% for track and 10%–15% for intensity. Some statistically insignificant decreases in track skill were observed at shorter lead times, but absolute errors were typically smaller at these times.

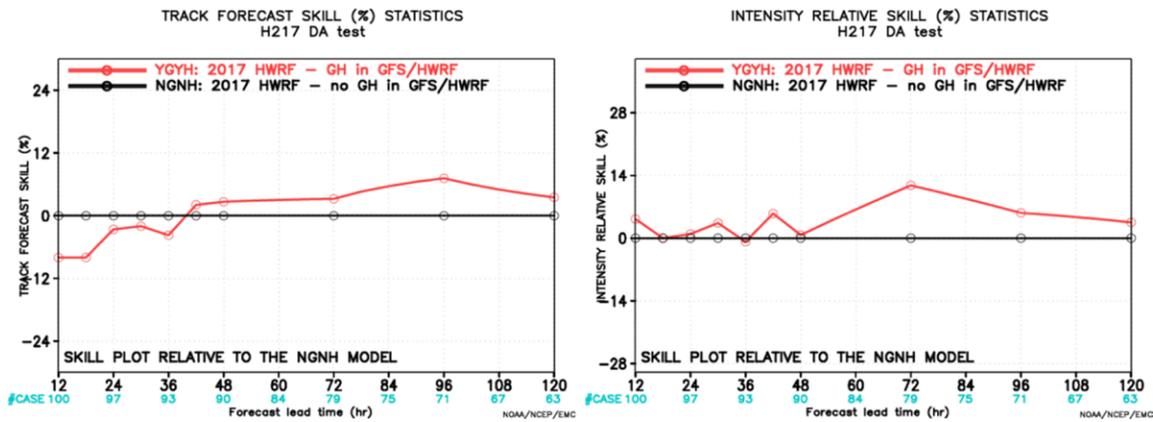


Fig. 7. Average impact of GH dropsondes on operational HWRf forecasts of track and intensity for the 2016 storms sampled by the GH (i.e., Gaston, Hermine, Karl, and Matthew). The results from adding GH dropsondes (red traces; coded YGYH) indicate improvements in the forecast skill for (left) track and (right) intensity relative to control runs performed assimilating all conventional observations including reconnaissance aircraft (black traces; coded NGNH). The results are taken from the conference presentation of Sippel et al. (2018).

These tests are being extended at AOML to evaluate the impact of the GH data on the 2019 operational HWRf, which further incorporates boundary conditions from the new finite-volume cubed-sphere (FV3) version of the GFS model. The results obtained thus far for the 2016 observations from Gaston, Hermine, and Karl, shown in Fig. 8, again show improvements in the track forecast at lead times of 84 h and beyond, and intensity at 72 h and beyond. The peak improvements exceed 10% for track and 20% for intensity. The improvements are again not statistically significant but closely follow the results from the earlier model version. The results of the two experiments are encouraging given the historical difficulties in demonstrating significant improvements to intensity forecasts (Rappaport et al. 2009).

To investigate the impact of GH dropsonde observations on forecasts in the event of a gap in polar-orbiting satellite coverage, initial tests used the 2015 version of the operational HWRf model (H215) and the Gridpoint Statistical Interpolation analysis system (GSI) assimilation system with the three-dimensional ensemble-variational hybrid assimilation scheme

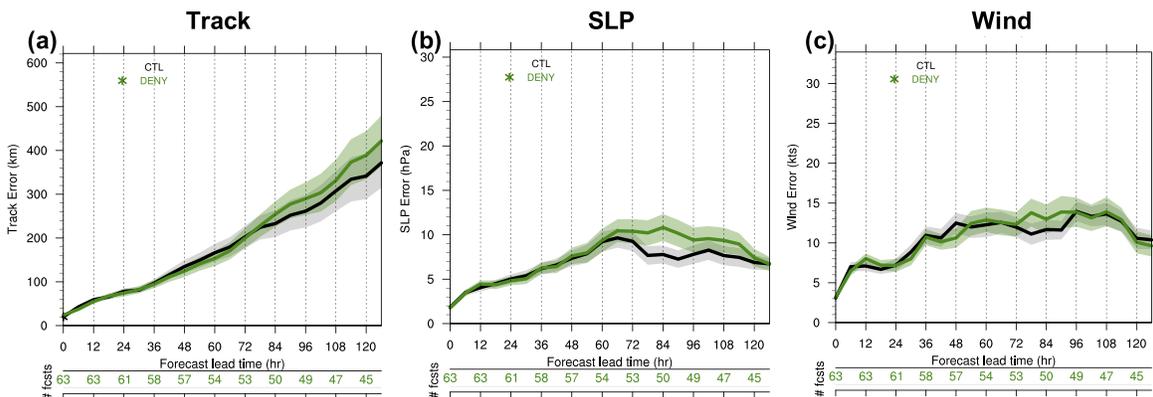


Fig. 8. Average absolute errors for CTL (black; with GH dropsondes assimilated) and DENY (green; no GH dropsondes assimilated) aggregated for TCs Gaston, Hermine, and Karl in 2016. Errors include (a) storm track (km), (b) minimum sea level pressure (hPa), and maximum surface wind speed (kt; $1 \text{ kt} = 0.51 \text{ m s}^{-1}$) as a function of forecast lead time out to 126 h. The number of forecasts (# fcsts) at each lead time is shown below each panel. Included in the average errors is the 1σ sample standard deviation of each experiment (black and green shaded regions). Although results are not statistically significant, a paired t test, accounting for correlated samples, was used to determine statistical significance between the two experiments. Results generated by A. Kren.

(operational through mid-2016; Wu et al. 2002; Kleist et al. 2009). The satellite gap was simulated by withholding sounding data from the Advanced Technology Microwave Sounder (ATMS) and Cross-track Infrared Sounder (CrIS) instruments onboard the *Suomi NPP* satellite in both the control and experimental model runs (as well as in the GFS forecasts used for HWRf boundary conditions). Similar data from other satellites were assimilated as usual. Results for Hurricane Matthew in 2016 (Fig. 9) showed large positive (but not statistically significant) track forecast impacts from addition of the GH dropsonde data, especially for model cycles where the observations were directly assimilated. Track forecast skill improvements averaged over all Matthew model cycles were consistently near 20% at lead times beyond 30 h, while intensity impacts were more mixed. For this single storm, the impact of the improved track forecast on predicted precipitation in the southeastern United States was notable (Fig. 10). Peak predicted rainfall near the coastline of the Carolinas was moved onshore in closer agreement with observations. The study did not directly examine the results relative to forecasts including the *Suomi NPP* data.

Additional studies with a research version of HWRf further support the potential for positive forecast impact from the dropsonde data and are facilitating initial evaluations of the impact of the remotely sensed data. These studies are using the Hurricane Ensemble Data Assimilation System (HEDAS; Aksoy et al. 2012, 2013), which uses an ensemble Kalman filter

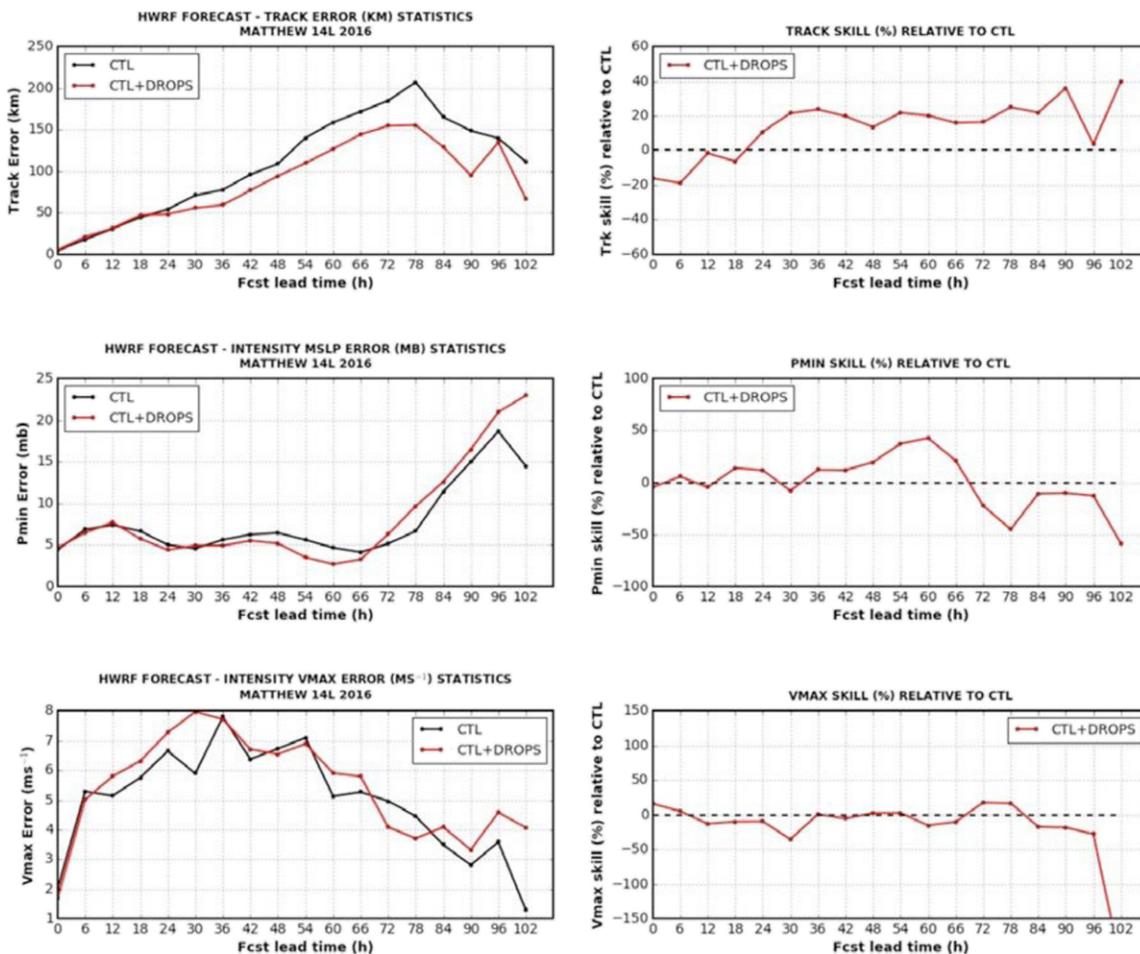


Fig. 9. Summary of GH dropsonde impact on the operational HWRf forecast of track and intensity for Hurricane Matthew when satellite observations were withheld from all model runs. Results shown are averaged over all forecast cycles during Hurricane Matthew. (top) Track error, (middle) error in minimum sea level pressure (PMIN), and (bottom) maximum wind velocity (VMAX). (left) Track and intensity forecasts with and without GH observations. (right) Corresponding change in forecast skill relative to the control (CTL) case with no GH observations. Results were generated by James Taylor.

to assimilate TC inner-core observations. In an evaluation of the impact of GH dropsonde observations from a composite of 10 storm systems, Christophersen et al. (2018a) showed that assimilation of the dropsondes had a positive impact on the initial analyzed storm structure, and the resulting track and intensity forecasts were generally improved by ~10%. The composite study was an extension of Christophersen et al. (2017) that demonstrated that the relative impact of GH dropsondes in the inner core and near environment varied depending on the presence of inner-core reconnaissance data from other aircraft.

A key benefit of using the HEDAS framework is simplified testing of the best approaches to assimilate the new remotely sensed data. Ongoing work [reflected by recent conference presentations by Christophersen et al. (2018b) and Sellwood et al. (2018)] is exploring the impact of HAMSr observations from 2016 and HIRAD observations of Hurricane Joaquin in 2015. The HAMSr data are observed to affect the initial HEDAS analysis, but the ultimate potential forecast impact is still unclear. To improve efforts to assimilate the HAMSr data, efforts are also ongoing to better characterize uncertainties in the data (see “Estimation of HAMSr error variances for data assimilation” sidebar). Assimilation of HIRAD wind speed retrievals within HEDAS improved the initial analyzed surface structure of Hurricane Joaquin and also positively impacted the forecasted track and intensity. Error in the forecasted track was reduced through 96-h lead time, while the intensity forecasts were improved through 36 h for the maximum wind speed and through 24 h for minimum sea level pressure.

Global-scale data impacts. The impact of the GH observations on the accuracy of the critically important operational global-scale weather forecasts is being evaluated using the GFS model. The tests are employing multiple recent versions of the model and examining impacts both in the presence of the full conventional observing system and with a gap in sounding data from the *Suomi NPP* satellite. Forecasts of both TCs and winter storms are being investigated.

Initial tests at EMC evaluated the impact of the GH dropsonde observations from 2016 on the track forecasts of all concurrent Atlantic basin storms using the 2017 operational version of GFS. This included all the storms present during the periods of the GH flights, specifically Gaston, TD8, Hermine, Karl, Lisa, Matthew, and Nicole. The impact was evaluated relative to assimilation of all conventional and standard reconnaissance observations. The results, shown in Fig. 11, reflect a large positive impact on the track forecast at lead times beyond about 36 h. The relative skill improvement peaks at around 14% for the 72-h forecast lead time but exceeds 10% for lead times greater than 48 h. The improvement at 72 and 96 h was statistically significant. The GH dropsonde impact on selected individual 2016 TC track

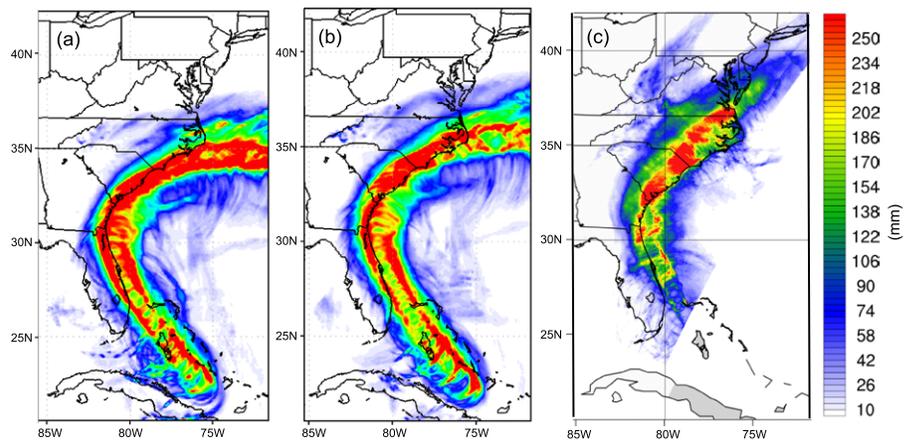


Fig. 10. Comparison of observed and HWRf-simulated precipitation for Hurricane Matthew demonstrating the impact of an improved track forecast. (a) HWRf-predicted accumulated precipitation for the control without GH data, (b) modified predictions following assimilation of the GH dropsondes, and (c) observations taken from the NCEP Stage 4 hourly precipitation imagery (Lin 2011). Both simulations were for the satellite gap scenario where sounding data from the *Suomi NPP* satellite were withheld. Addition of the GH dropsondes resulted in a forecasted track closer to the coastline in the Carolinas and more overland precipitation, in better agreement with observations. Graphics provided by James Taylor.

forecasts was dramatically greater than the average over all forecast cycles at lead times beyond about 48 h. Forecasts of Hermine and Gaston exhibited statistically significant track improvements in excess of 20% over several lead times. The results also showed substantial

Estimation of HAMS R error variances for data assimilation

Assimilation of the observations into forecast models requires understanding and specifying the error characteristics of the data. For a new dataset like HAMS R, those characteristics were not well understood, and the large number of collocations between the retrieved profiles and dropsondes provided an opportunity to derive quantitative error variance estimates. Collocated temperature and specific humidity profiles from HAMS R, the dropsondes, as well as the ECMWF ERA5 (Copernicus Climate Change Service 2017) global reanalysis and HWRF analysis spanning the 2016 HRR flights, were employed in a “three-cornered hat” (3CH; as in Anthes and Rieckh 2018) analysis yielding simultaneous solutions for the error variance for different combinations of three of the four products.

The HAMS R inputs were drawn from bias-corrected retrievals on 25 pressure levels provided by Shannon Brown at JPL. Retrievals within 60 min of a dropsonde launch were considered, and the profile closest in time and location to the dropsonde release location were selected. A spatial–temporal correction algorithm was applied to the HAMS R retrievals similar to Gilpin et al. (2018); any effects of spatial and temporal differences are expected to be minor. The majority of the resulting profiles were within 5 min and 40 km of the dropsonde release. Of 634 available dropsonde soundings, 533 collocations were obtained. The original, high-resolution, dropsonde data were vertically interpolated to the same pressure levels and the ERA5 and HWRF analyses were interpolated in time and space to the dropsonde location as well as vertically to the pressure levels.

Following Anthes and Rieckh (2018), three different linearly independent equations are constructed and solved simultaneously for the error variance for different combinations of the collocated products. Error covariances among the datasets were assumed negligible compared to mean differences between the datasets. In contrast to Anthes and Rieckh (2018), bias terms capturing the mean differences between the datasets were included. The differences between the datasets were normalized using the mean ERA5 profiles at each dropsonde location and time. The GH dropsonde data were most likely assimilated within the ERA5 so those two results are not entirely independent, but the GH data represent a very small fraction of the assimilated data and the relevant conclusions should not be significantly affected.

Profiles of the derived HAMS R and dropsonde error variances for the different combinations are shown in Fig. SB2. Error variances for ERA5 and HWRF were generally smaller than those for the dropsondes and are not shown. The results confirm that error variances are generally small for the well-characterized dropsonde data. The HAMS R error variances exhibit vertical structure and are elevated relative to the dropsondes, demonstrating that it is not appropriate to simply assimilate the retrieved HAMS R profiles as if they were dropsondes. Accurately capturing these characteristics should facilitate improved assimilation of the data. Further refinements to the HAMS R temperature and humidity retrievals are currently being generated by JPL and will be similarly analyzed.

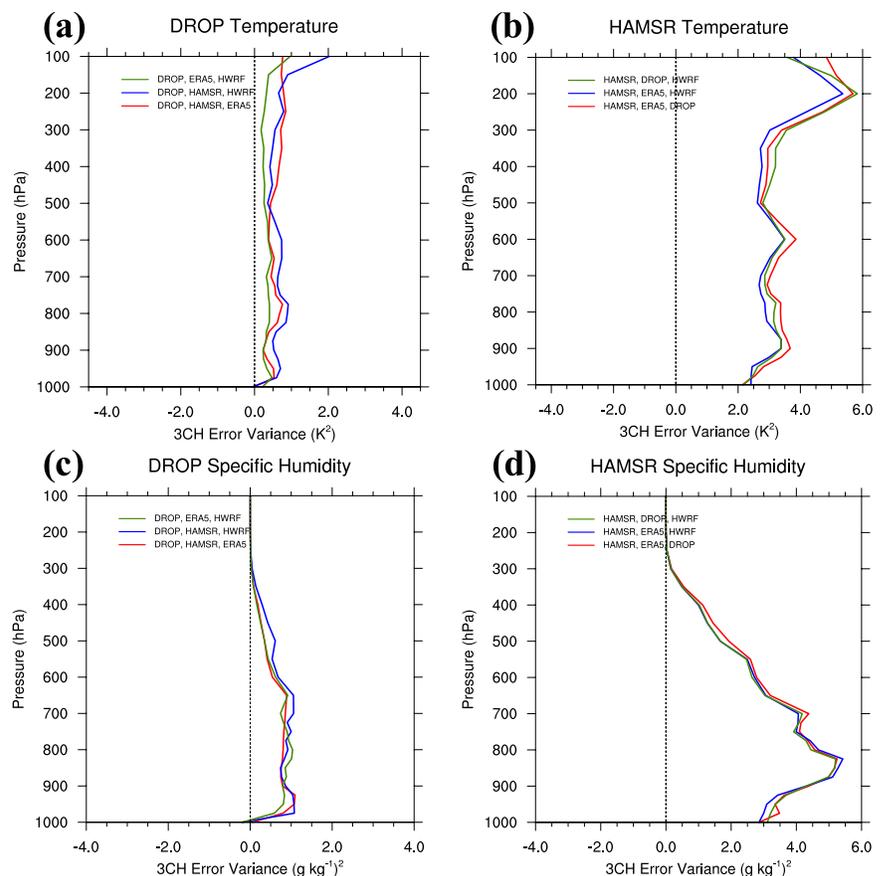


Fig. SB2. Estimated three-cornered hat (3CH; as in Anthes and Rieckh 2018) error variance of (a),(b) temperature (K^2) and (c),(d) specific humidity [$(g\ kg^{-1})^2$] using three independent equations based on collocations of four datasets for all 2016 tropical cyclone cases during SHOUT. Results are shown for the (a),(c) dropsondes (DROP) and (b),(d) HAMS R retrievals. In contrast to Anthes and Rieckh (2018), we include bias terms in the estimated error variances, which are simply the mean differences between the datasets.

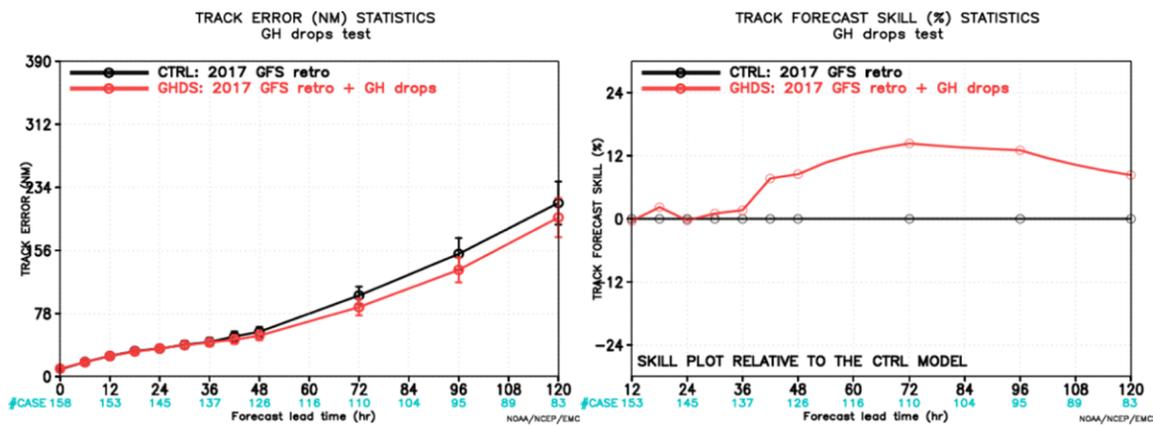


Fig. 11. Impact of GH dropsonde measurements (GH drops) on the track error of North Atlantic storms within the 2017 operational GFS model. The results represent an average over the forecast cycles spanning from the first Gaston flight through the end of Gaston and the first Karl flight through the end of Matthew. All storms during these periods (listed in the text) are incorporated, whether or not they were directly sampled by the GH. (left) Track error with (GHDS; red) and without (CTRL; black) the GH dropsondes. (right) Corresponding impact of the GH dropsondes on track forecast skill. The results are taken from the conference presentation of Sippel et al. (2018).

improvements in the track forecasts of concurrent Pacific cyclones based on observations of the Atlantic storms, suggesting that the GH dropsonde observations could have positive larger-scale impacts (not shown).

Ongoing work at EMC is extending the analyses of the GH dropsonde impact to the new FV3-GFS model. Results are still preliminary, but the positive forecast impacts continue with the new operational model. A future publication is planned by EMC to document these results.

Kren et al. (2018) examined the impact of the GH dropsonde observations of Hurricane Matthew both with and without a gap in satellite observations using the 2017 operational version of the GFS. Those results further echoed the potential for positive forecast impact, showing GFS track error reductions of 7%–30% after 60-h lead time with statistically significant reductions in the 72–84-h lead times for data added to the full observing system, and statistically significant track error reductions of 14%–20% at 72 and 90 h when *Suomi NPP* satellite sounding data were withheld. Kren et al. (2018) also explored the impact of the GH dropsondes from the 21–22 February ENRR flight on over both a verification region in southern Alaska and the southeastern United States, where a severe weather outbreak occurred on 23–24 February 2016. While observation impacts were insignificant over Alaska, marked forecast improvements were observed over the southeastern United States both with and without a simulated gap in satellite coverage.

Other independent SHOUT-supported OSSE studies examined the impact of simulated dropsonde observations on forecasts of Pacific wintertime storm systems (Peevey et al. 2018; English et al. 2018) using the GFS model and ECMWF T511 Nature Run (Masutani et al. 2007). Among the most relevant findings, targeted dropsondes in the presence of a satellite gap provided improvements for about half of the forecasts analyzed. These dropsondes could not compensate for degradations in global average forecasts but could potentially compensate for specific targeted storms.

Summary and future outlook

The NOAA UAS Program’s SHOUT project successfully conducted three GH field campaigns and supported a suite of ongoing data impact studies in pursuit of its goals to evaluate the ability of observations from HALE UAS to improve forecasts of high-impact weather events like TCs or mitigate potential degradation of forecasts in the event of a future gap in satellite coverage.

During the 2015 Hurricanes, 2016 El Niño Rapid Response (ENRR), and 2016 Hurricane Rapid Response (HRR) campaigns, the GH aircraft proved to be an effective platform for addressing the various SHOUT scientific objectives. The instrument performance was generally reliable (with the exception of some early issues with the dropsonde launcher) and the adaptive sampling techniques for targeting dropsonde observations that were employed proved effective in helping to guide missions. Data collected during SHOUT have been extensively used in impact studies and were also utilized in real time by forecasters at NOAA NHC.

While the limited number of storms analyzed make it difficult to establish statistical significance, the results from several diverse but complementary studies consistently demonstrate the potential for positive forecast benefits from assimilating targeted observations from the GH during high-impact weather events. The results obtained at EMC with different versions of the operational modeling systems, in particular, are highly positive and argue for the potential merit of these unique observations. The observed benefits span both regional and global models. The analyses ultimately performed did not fully address the ability of the observations to mitigate a satellite gap, but instead focused on the broader observation benefit.

Ongoing studies are continuing to expand the analyses to make the greatest possible use of the available observations. These include incorporating more of the observed storms both during SHOUT and the collaborative HS3 and EPOCH campaigns to increase sample sizes, using additional current forecast models, and more fully evaluating the impact of the remotely sensed data. The coverage of the remotely sensed observations offers potential that has yet to be fully exploited. One objective of these studies is to better understand which of the GH observations (based on their altitude, location, etc.) are having the largest forecast impacts. A specific example is determining if observations from regions with identified increased forecast sensitivity are, indeed, having a greater positive impact on the forecasts.

To fully demonstrate statistically significant forecast impacts, observations of more storms over a longer period are ultimately needed. Tests with an experimental platform over fixed deployment periods are inevitably limiting, but are a necessary first step to justifying further investigation. Presently, there are no immediate plans for NOAA to employ a HALE UAS like the GH operationally. While any future considerations on the operational utilization of HALE UAS will incorporate budgetary and programmatic, as well as scientific considerations, the potential for scientific benefit is broadly supported by the success of the SHOUT field campaigns and the positive impacts of SHOUT GH observations on numerical forecasts of high-impact weather events.

In the near term, one of the greatest legacies of SHOUT is the application of new targeting approaches. The results and lessons learned from SHOUT are being applied to refined tasking of traditional aircraft in NOAA's operational TC synoptic surveillance missions. The methods developed and tested during the SHOUT TC campaigns have evolved into a currently funded NOAA Joint Hurricane Testbed project and were used semioperationally by NHC to develop G-IV flight patterns.

Acknowledgments. Many individuals contributed to completing all of the components of the SHOUT project and their contributions are all greatly appreciated. Dr. Sandy MacDonald had an early vision for use of the GH for operational weather forecasting and was instrumental in securing initial SHOUT support. Flight operations were supported by many groups including those at NASA AFRC, NASA WFF, Northrop Grumman, the NOAA Aircraft Operations Center (AOC), NOAA UAS Program Office, and the mission scientists from the SHOUT science team. The leadership efforts of Frank Cutler (NASA AFRC), CDR Jonathan Neuhaus (NOAA AOC), and program managers Phil Kenul and John "JC" Coffey were especially significant. Additional operational assistance was provided by Aaron Duley at NASA Ames through support for the NASA Mission Tools Suite (MTS) and the University of Wisconsin under Chris Velden through provision of critical satellite-based situational awareness products. The critical

data sets were produced by dedicated instrument teams led by Terry Hock from NCAR/EOL (AVAPS), Dr. Bjorn Lambrigtsen and Dr. Shannon Brown from NASA JPL (HAMSR), Dr. Gerald Heymsfield from NASA GSFC (HAMSR), and Dr. Richard Blakeslee from NASA MSFC (LIP). SHOUT was funded through the NOAA UAS Program Office and the Disaster Relief Appropriations Act of 2013. Partial funding support was provided through the Cooperative Agreement NA67RJ0149 between NOAA and University of Miami. The constructive comments of three anonymous reviewers were very helpful in improving this paper and are sincerely appreciated.

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